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Metal Halide Lamp with Enhanced Red Emission

Background of the Invention

The invention relates to a metal halide discharge lamp for the generation of visible radiation. Metal halide lamps have been found desirable for many illumination applications due to their high efficacy, good general color rendering and high luminosity. Products of a wide range of lumen output and color temperature are commercially available. However, standard commercial lamps do not render red colors well as compared to incandescent light sources, which behave very closely to ideal blackbody radiators. The lamps of the present invention can be used in applications where the red rendering feature is of importance such as the illumination of fresh produce and meats or clothing and furniture or cosmetics, beauty shops and fashion retailing or paint and art retailers as well as entertainment establishments.

As specified by the Commission Internationale de l'Éclairage (CIE) in CIE publication number 13.2, the R_9 color rendering index represents a comparison between the reflected intensities of a standardized red test sample when viewed separately with two light sources, a test source and a reference source. For test sources of CCT less that 5000K the reference source is blackbody radiation of equal corre-

lated color temperature (CCT) and illuminance. The more identical the two reflected intensities from the red test sample, the higher the R_9 value. A maximum value of 100 represents a light source that renders the specified red test sample identically to the reference source. An R_9 value less that 100 represents a light source that emits either less or more red emission as compared to the reference source. This convention is very difficult to work with when comparing red color rendering since the R_9 values give no indication whether a test source is diminished or intensified in red emission. To indicate cases where an R_9 measurement represents a lamp enhanced in red as compared to a blackbody standard, data in the detailed description of the invention is presented as 100 + x where x represents the number of points of enhancement. This is not the standard notation but has proven much easier to work with. For example, if a test lamp is 20 points more red enhanced than the equivalent blackbody source, it will be referred to as 100 + 20 instead of the strictly proper value of 80 that cannot be distinguished in R_9 value from a lamp 20 points diminished in red. Without this notation, cumbersome graphical methods utilizing complicated color space definitions are required.

Most commercial metal halide light sources are significantly weak in red emission with negative R_9 values being common, especially for lamps with CCT

<4000K. Typically, quartz arc tubes produce lower R_9 values than equivalent ceramic arc tubes. The output spectrum of a metal halide lamp is generally determined by the distribution of metals present in the gas phase at operating temperature and pressure conditions. Typically, metal halide lamps operate in a "saturated" condition, that is during operation some of the metal halides vaporize, but there is sufficient quantity present such that excess liquid or solid metal halides are still present. The overall quantity and distribution of metals in the gas phase is generally determined by the vapor pressures of the metal halides at the coldest temperature inside the arc tube body. In general, higher metal halide vapor pressure results in increased emission of the corresponding metal element. Based on experimental observation of the output spectrum, it has been noted that with certain mixtures of metal halides, some metals are present in the gas phase at a higher proportion than expected according to the known independent vapor pressures of the corresponding metal halides. R. Lorenz ("Lighting Research & Technology", Vol 8, number 3, 1976, pp. 136-140) has explained this phenomenon with a theory of metal halide complexing. Essentially, a metal halide of low vapor pressure can react with a metal halide of high vapor pressure and high reactivity to produce a metal halide complex of higher vapor pressure than the reactant low vapor pressure metal halide. In

this way the emission of a metal halide of low vapor pressure can be significantly increased in a metal halide lamp. The complexing phenomena is important to the invention in that it provides for significantly more calcium radiation than possible with the independent vaporization of CaI_2.

PRIOR ART

U.S. patent application, serial No. 09/427,305 "A Metal Halide Lamp with Enhanced Red Emission, in Excess of a Blackbody", (and owned by the same assignee as the present invention) describes a lamp of similar objective but different technology. The disclosure describes a lamp that has a shroud of neodymium-doped glass to block transmittance of yellow radiation centered near 585nm. The lamp also requires the use of metal heat shields and a vacuum outer jacket for maximum effectiveness. These features may make the lamp undesirable from a manufacturing viewpoint and the vacuum outer jacket presents a potential safety issue requiring more design considerations than a gas filled outer jacket. The elevated seal temperatures that result from the heat shielding are also a concern for long lamp life.

U.S. patents 4,027,190 to Shintani et al. and 4,360,758 to Thornton, Jr. et al. describe metal halide lamps that use calcium halides complexed with halides to achieve improved R_9 and general color rendering values. U.S. patent 4,742,268 to Caruso et al. describes a metal halide lamp which utilizes

SnI_2 + CaI_2 complexing and an ellipsoidal shaped quartz arc tube for exceptional color rendering. Processing steps that eliminate moisture from the hygroscopic calcium iodide are also described. U.S. patent 4,801,846 to Kramer et al., describes the addition of calcium iodide to sodium iodide + rare earth iodide chemistries for enhanced red emission. U.S. patent 5,256,940 to Wada et al., describes the use of aluminum halides for complexing Na/Tl/In/Sn/Li halide chemistries to create a lamp of improved color rendering capability. U.S. patent 5,461,281 dated 10/24/95 to Fromm et al., describes as an example the use of AlI_3 as a getter material used to react with oxygen in an arc tube to prevent the attack of electrodes by metal halides. U.S. patent 6,031,332 to Wijenberg et al., describes the addition of CaI_2 to NaI + rare earth iodide chemistry to reduce crest factor and improve life. U.S. patent 6,005,346 to Shaffner describes a metal halide lamp without NaI and mercury which produces a spectrum highly saturated in primary colors for use as projection light source. Japanese Patents JPN PAT S52-120585 1977 and JPN PAT S52-031583 1977 laid open but not claimed by Toshiba corporation mention the use of Ca, however they do not mention enhancement of Ca red emission by complexing of Ca halide with the halides of Al or Ga. The role of Tl halide in suppressing atomic Ca blue radiation is not de-

scribed nor is enhancing molecular Ca monohalide red radiation.

The journal "Lighting Research & Technology" vol 8, number 3, 1976, pp. 136-140 contains an article by R. Lorenz titled "Improvement of metal halide lamps by complex formation which presents a scientific explanation of metal halide complexing and provides some experimental data demonstrating the effect with metal halide lamps of various chemistries.

Summary of the Invention

In order to produce a metal halide lamp of increased red emission, CaI_2 is added to the arc tube chemistry to provide radiation the wavelength range 610nm-650nm which is optimal for improved red rendering as measured by the R_9 color rendering index. Due to the low vapor pressure of CaI_2, a complexing agent of AlI_3 or GaI_3 is also added to significantly increase the amount of calcium in the gas phase and thereby increase red radiation. TlI is also included in the fill chemistry in order to suppress blue radiation and preferentially enhance red calcium atomic and molecular radiation. Optionally, a bandwidth filter centered about 585nm can be used to reduce yellow radiation and further enhance the proportion of red emission while maintaining a sufficiently white light source.

The metal halide lamp having superior red rendering characteristics comprises an arc tube formed

of a material transmissive to visible radiation made from either polycrystalline alumina, sapphire or quartz.

The arc tube contains a fill of metal halides and CaI_2 or $CaBr_2$ plus AlI_3, $AlBr_3$, GaI_3 or $GaBr_3$ plus TlI or TlBr. The CaI_2 or $CaBr_2$ or both are in a molar quantity between about 10 and 75% of the total molar quantity of the total halides and the AlI_3 or $AlBr_3$ or both are in a molar quantity between about 2 and 50% of the total molar quantity of the total halides. The TlI of TlBr or both are in a molar quantity between about 5 and 50% of the total molar quantity of the total halides. The fill further includes mercury plus either Ar or Xe. Halides of at least one of the elements of Dy, Ho, Tm, Na, Li, Cs may be further included.

The object of the invention is to provide a metal halide lamp with significant improvement in its ability to render red colors. This is desirable for lighting retail spaces and foods such as meat, fish and produce. The appearance of human skin is also enhanced by improved red emission. The lamp can be used alone or in combination with standard light sources to improve overall red color rendering.

Another object of the invention is to provide a metal halide lamp with superior red rendition that is identical in construction to commercially available lamps of equal power.

Yet another object of the present invention is to provide a metal halide lamp that is easily manufactured with existing standard manufacturing equipment.

Still another object of the present invention is to provide a metal halide lamp with superior red rendition and acceptable efficacy as well as general color rendering index and whiteness (i.e. no particular hue) so that it can be employed in general illumination applications.

Another object of the invention is to provide a light source of highly saturated primary colors (red, green and blue) which can be used for projection lighting with less filtering requirement than conventional metal halide and high pressure mercury lamps. This allows for increased system efficacy and/or an enlarged color gamut.

Brief Descriptions of the Drawings

Fig. 1 shows the construction of a typical ceramic metal halide lamp for general illumination purpose.

Fig. 2 shows the photopic eye sensitivity transmission curve, R_9 reflectance curve, and Nd doped glass transmission curve.

Fig. 3 shows performance effects of $CaI_2 + AlI_3$ additions to a typical 3000K CCT ceramic metal halide chemistry.

Fig. 4 shows the red enhanced performance and spectra achieved with the use of a Nd doped filter

shroud for lamps of 3000K chemistry, with and without additions of CaI_2 and AlI_3.

Fig. 5 shows the red enhanced performance and spectrum achieved with a tri-component metal halide chemistry of CaI_2, AlI_3 and TlI.

Fig. 6 shows the effect of thallium iodide dose amount on spectral distribution for a CaI_2-AlI_3-TlI fill chemistry.

Detailed Description of the Preferred Embodiments

Fig. 1 shows a typical embodiment of the invention for general lighting applications. A polycrystalline alumina (PCA) arc tube **1** is housed in an outer jacket **2** of hard glass. The volume inside the jacket **3** may be evacuated or filled with nitrogen. Lamp current is conducted to and from the lamp by means of electrical feedthroughs **4a**, **4b** that are hermetically sealed into the arc tube **1**. A tubular shroud **5** surrounding the arc tube **1** is made of hard glass or quartz and may optionally be doped with neodymium to significantly absorb visible radiation in a yellow bandwidth centered near 585nm as shown in Fig. 2. For a lamp designed to operate at 150W, the arc tube **1** contains a fill **6** of 9-14 mg Hg, 100-300 torr Ar, and metal halides including CaI_2 for red emission and AlI_3 or GaI_3 for formation of Ca containing halide complexes. The formation of calcium-aluminum iodide complexes with vapor pressures higher than those of independent calcium iodide is important in increasing calcium in the vapor phase

for more calcium red emission. Typically, TlI is included in the metal halide dose to provide green radiation for balanced color and high efficacy. TlI also serves a role in influencing calcium to emit preferentially in the red region of the spectrum.

By analyzing the spectra in Fig. 2, the key advantages of the invention can be understood. The R_9 reflectance curve shows that the reflectance of spectral emission increases greatly as wavelength exceeds ~ 610nm. However, the photopic eye sensitivity curve shows that the sensitivity of the eye decreases rapidly as wavelength increases beyond 555nm. the calcium emission seen in Fig. 3-5 between ~ 615nm - 650 nm is very effective in improving red rendering because it will reflect strongly from a red object but still be considerably visible to the human eye. Some commercial metal halide lamps include lithium halide in the fill in an attempt to improve red rendering. The predominant Li atomic emission line at 671nm is scarcely visible to the human eye and of limited effectiveness. 611nm Li atomic radiation is effective but typically not strong in a metal halide lamp.

In all embodiments of the invention, calcium radiation in the 615-650 region of the spectrum is the primary method of boosting red emission. There are several atomic calcium radiation lines tightly grouped in the 616nm - 617nm range and also in the 644nm - 650nm range. However, an even larger con-

tribution of red radiation comes from calcium monoiodide molecular radiation in the 623-651nm range.

In all embodiments of the invention either AlI_3 or GaI_3 are included in the fill chemistry with the intent of acting as both a complexing agent and as a broadband radiator of visible emission. Since Al and Ga are successive elements in the periodic table and chemically similar, both AlI_3 and GaI_3 were tested and found to be effective in combination with calcium iodide. However AlI_3 is believed to be preferable due to its higher reactivity, which makes it a more preferable complexing agent. Also, AlI_3 is believed to be more chemically compatible with a PCA arc tube and of lower cost than GaI_3.

TlI serves an important role in the fill chemistry of the invention. It has been observed that increasing dosage of TlI affects R_9 performance by suppressing calcium radiation in the blue 380-450nm range and favoring calcium emission in the 615-650nm range. It is believed that through significant self-absorption, Tl 377.7nm atomic radiation becomes self-reserved and creates a broad absorption notch that is increasingly widened into the visible blue wavelength with increasing TlI dose. This effect provides a very useful mechanism to limit radiation in the blue region in order to increase R_9, lower CCT, or balance spectral output to provide a white light source. The effect of TlI dose size on spec-

tral output can be seen graphically in Fig. 6 for a CaI_2-AlI_3-TlI fill chemistry. In Fig. 6 the calcium to aluminum molar ratio is kept constant while the Tl molar ratio is adjusted. Clearly, blue radiation from 380-450 nm is suppressed as Tl dose is increased.

In some embodiments of the invention, it is desirable to increase R_9 by use of a neodymium-doped shroud 5. Fig. 2 shows the transmission spectrum of this filter used to absorb yellow radiation centered ~585nm. A shroud of glass doped with Nd is used to create an absorption band ~30 nm wide at half peak intensity. This reduction of yellow radiation increases R_9 by making the red emission proportionally larger without significantly increasing Duv. Nd doped glass is a commercially available product. Many commercial metal halide lamps commonly use a clear shroud to reduce arc tube heat loss, absorb ultraviolet radiation, and shield non-passive arc tube failures. A clear shroud can be easily substituted with a Nd doped version. Typically, the glass used is a borosilicate product of high silica content suitable for high temperature operation.

Table 1 identifies and gives performance data for some experimental embodiments of the invention as well as data from some standard commercial lamps for comparison. Figures 3-5 show spectral intensity graphs from some of these same lamps. All lamps except lamp E are identical in construction within

normal fabrication tolerances except for the altered chemistry and Nd doped shroud in specific lamps as noted. Lamp E is of nearly identical construction but with a cylindrical shaped arc tube instead of the tapered design of lamps A-D and F-H that is shown in Fig. 1. All lamps were designed for and operated at 150W.

TABLE I

Lamp	LPW	CRI	CCT	Duv	R9
(A) Std 3000K Chemistry	86	84	2937	-4.1	-18
(B) Std 300K Chem + CaI_2 + AlI_3	77	93	2960	-6.3	53
(C) Std 3000K Chem + Nd doped shroud	68	91	3392	-2.2	74
(D) Std 3000K Chem + CaI_2 + AlI_3 + Nd doped shroud	65	88	3174	-5.5	100+29
(E) Std 4300K Chemistry	83	91	4239	2.2	40
(F) CaI_2 + AlI_3 + TlI Chemistry	66	67	4087	-3.7	100+130
(G) CaI_2 + AlI_3 + TlI + DyI_3 + NaI Chemistry	72	84	3776	-2.4	100+48
(H) CaI_2 + AlI_3 + TlI Chemistry + L:I	67	80	3601	-8.6	100+70

Lamp A is a standard 3000K commercial ceramic metal halide product with a metal halide chemistry

of sodium iodide, thallium iodide, lithium iodide and rare earth iodides of dysprosium, holmium and thulium. Lamp B represents the first embodiment of the invention and contains doses of 6.8 μmole/cm^3 CaI_2 and 2.5μmole/cm^3 AlI_3 added to the standard commercial ceramic metal halide chemistry of lamp A. In Fig. 3, the spectra of lamps A and B are plotted for comparison. For lamp B, proportionally more emission in the red (610-650nm) region can be observed.

Lamps C and D are identical to lamps A and B respectively except for the tubular shroud 5 that surrounds the arc tube 1. For lamps C and D, a high silica borosilicate glass shroud appropriately doped with Nd and Ce to provide the spectral distribution curve seen in Fig. 2 is substituted for the standard clear shroud. As seen in Fig. 4, this provides an absorption notch in the spectra that increases the proportion of red emission in the spectra to increase the R_9 value without largely altering Duv or CCT. From data in Table 1, efficacy is reduced in lamps C and D by about 21% and 16% respectively when compared with lamps A and B. Lamp D represents a second embodiment of the invention. High silica borosilicate glass doped with Nd and Ce is a commercially available product. It is the Nd doping which provides for the absorption notch in the spectrum centered near 585nm and is essential for the second embodiment of the invention. Cerium doping of

shroud glass in metal halide lamps is a common practice in order to block the transmission of ultraviolet radiation. The tubular shroud used in lamps C and D is 19mm in inner diameter with a wall thickness of 1.5mm.

Lamp E is a standard 4300K commercial ceramic metal halide product with a metal halide chemistry of sodium iodide, thallium iodide and rare earth iodides of dysprosium, holmium and thulium. Lamp F is a third embodiment of the invention and utilizes a sodium-free tri-component metal halide chemistry of 6.8 μmole/cm^3 CaI_2, 2.5 μmole/cm^3 AlI_3 and 1.5.μmole/cm^3 TlI. This results in a lamp of CCT near 4000K with greatly intensified red emission as compared to an incandescent source of equal CCT. In this case, no filter is required to remove yellow radiation from the spectrum because a natural notch in the spectrum exists without sodium in the chemistry. This effect can be seen in Fig. 5 which compares the spectra of lamps E and F. In Table 1, Lamp F is measured as having an R^9 value 100 + 130. This is a quite extreme value and in many lighting applications more moderately enhanced red radiation is desired. The R_9 oversaturation of a lamp F type chemistry can be reduced to a lower level for various application by adding DyI_3 or other rare earth halides, adding NaI, and adjusting the dosage of TlI.

Lamp G of Table 1, represents a fourth embodiment of the invention which has lower R_9, higher efficacy and higher CRI than Lamp F. Lamp G contains a metal halide chemistry of 6.8 μmole/cm^3 CaI_3, 2.5 μmole/cm^3 AlI_3, 2.4 μmole/cm^3 TlI, 0.6 μmole/cm^3 DyI_3, and 0.4 μmole/cm^3 NaI.

Other metal halides may be added to a lamp F type chemistry for purposes such as reducing CCT. For example, LiI can be added to the chemistry of lamp F to lower CCT as shown in Lamp H of Table 1. Lamp H represents a fifth embodiment of the invention and contains a metal halide chemistry of 6.8 μmole/cm^3 CaI_2, 2.5 μmole/cm^3 alI_3, 1.5 μmole/cm^3 LiI.

The sealing frit used to hermetically seal the electrical inlets **4a and 4b** into the arc tube **1** of a ceramic metal halide lamp typically includes dysprosium oxide to resist chemical attack by the rare earth halides typically found in a commercial ceramic metal halide lamp. When using a chemical fill that does not contain rare earth halides, such as embodiment 3 (lamp F), substitution reactions may occur between dysprosium oxide and metal halides in the fill chemistry. This will result in the introduction of DyI_3 into the fill chemistry and the partial loss of original fill material. Such changes in fill chemistry are likely to alter spectral output over lamp life and result in undesirable shifts in color. To avoid such reactions, inclusion of DyI_3 in the fill chemistry is recommended. If DyI_3 is not

desired in the lamp chemistry for performance reasons, an alternative sealing frit can be developed which does not contain dysprosium oxide but is chemically compatible with CaI_2, AlI_3, and TlI.

In addition to being an excellent red rendering light source for general illumination, the invention is excellent at rendering the other primary colors of green and blue as well. Embodiment 3 of the invention is especially effective in concentrating radiation in the primary red, green and blue regions of the spectrum for use in projection display devices. This can be seen in the spectrum of lamp F as shown in Fig. 5. Little radiation will be lost by the yellow, cyan and magenta notch filters typically used for projection display systems. The output spectrum of the invention can be utilized to efficiently yield a large color gamut capable of producing an exceptionally vivid color display as described by Shaffner in U.S. patent 6,005,346.

For simplicity of explanation all descriptions of the metal halide chemistries utilized in the invention have referred to as metal iodides but it is within the intent of the invention to substitute metal bromides for the described metal iodides to obtain similar results.

In my invention I claim: